ULTRA-STABLE OSCILLATORS FOR PLANETARY ENTRY PROBES

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Abstract

Ultra-stable oscillators on-board planetary missions were developed for Radio Science instrumentation, functioning as frequency references for the one-way downlink during atmospheric occultations. They have also been flown on planetary entry probes including the Jupiter entry probe, carried by Galileo, and the Huygens Titan entry probe, carried by Cassini, for performing Doppler Wind Experiments. The Jupiter and Titan probes utilized different oscillators, quartz and rubidium, respectively. This paper presents the development of ultra-stable oscillators on deep space missions and discusses the tradeoffs encountered when selecting oscillators for planetary entry probes, including factors such as duration of the experiment, the available warm-up time and the Allan deviation and phase noise requirements.

1. Introduction

The first Ultra-Stable Oscillators (USO) in deep space were flown onboard the Voyager spacecraft in order to meet the stability requirements of Radio Science experiments. These occultation experiments investigated the atmospheres and rings of the outer planets in a one-way downlink mode in order to eliminate the time needed by the transponder to lock-up on the uplink during an occultation egress as well as the media effect on the uplink. A single-string USO augmented the redundant telecommunications subsystem in each spacecraft [1]. The Voyager 2 USO is still working and the Voyager 1 USO ceased operations nearly 20 years after its procurement, exceeding specifications. Quartz crystal resonators, relatively small in mass, volume, and power, have been easier to qualify for deep space than atomic clocks. Since quartz, abundant in nature and efficient to grow, has the piezoelectric property as well as low loss characteristics, all ultra-stable oscillators in deep space have been quartz-based with the exception of the Huygens probe USO.

2. Oscillators on NASA Deep Space Missions

The Voyager Radio Science team worked closely with Frequency Electronics Inc. to procure five flight-qualified quartz ultra-stable oscillators. These oscillators had dual-ovens, AT-cut crystals with a typical Allan deviation of 1×10^{-12} for an integration time of $\tau = 100$ seconds. USO serial #4 was later flown on the Galileo spacecraft. The Galileo entry probe carried by the Galileo orbiter and released into Jupiter's atmosphere, was also equipped with a USO procured from the same vendor at a later time. Since then, several deep space missions have carried USOs for Radio Science experiments (e.g. Mars Global Surveyor, Cassini). These oscillators were single-oven, SC-cut crystals with a typical Allan deviation of 1×10^{-13} at $\tau = 100$ s. More recently, a flight-qualified USO is being prepared for proximity communications and navigation on the upcoming Mars Reconnaissance Orbiter mission. While AT-cut crystals are more common for commercial applications, the more expensive SC-cut crystals have been used more often recently for special applications such as USOs. The SC-cut crystals can provide a faster warm-up time, making them the better choice for entry probes.

3. The Huygens Ultra-Stable Oscillator

The ESA Huygens probe to Titan, carried by the Cassini spacecraft, has a Doppler Wind Experiment (DWE), a Radio Science experiment with requirements that were met with a rubidium (Rb) atomic standard [2]. Three reasons contributed to the selection of a rubidium USO:

i. A rubidium USO does not need to warm up very long before reaching adequate stability. The scientific goal of the investigation did not require reconstruction of the wind speeds on Titan to the 1 mm/s level, but could be compromised by residual oscillator drift in the descent data. Given that there were only 30 minutes of USO warm-up time available, it was realized that this would not be sufficient for a conventional quartz USO. Ironically, longer warm-up times are now being considered by the Huygens project in order to produce a lower sub-carrier frequency. This measure effectively reduces the Doppler shift on the telemetry, thereby improving the bit recovery rate [3].

ii. A rubidium USO is thought to be more robust with respect to the kind of accelerations expected during atmospheric entry and the fairly wide range of temperatures expected during descent. The Doppler Wind Experiment is different from the standard radio occultation experiment, where the environmental conditions on the spacecraft are more stable. The DWE team was concerned that a quartz USO would be stressed and then start to drift in an unpredictable way.

iii. As an atomic standard, the output frequency of a rubidium USO is tied to the frequency of the rubidium atomic transition, thus one obtains an absolute measurement of the received signal, rather than only a relative measurement. In order to determine the winds on Titan to the 1 m/s level, the DWE measurement requires only a rather modest 10^{-10} stability (precision) compared to the typical 10^{-13} stability of quartz.

4. Influences on Oscillator Performance

The performance of an oscillator is described by accuracy, reproducibility and stability. Accuracy, a measure of how well the oscillator relates to the definition of a time standard such as the second, and reproducibility, a measure of the ability of independent devices to produce the same value, are less important to Radio Science experiments than stability. Stability is a measure of how well the oscillator can generate the same frequency over a given period of time or, more precisely, a statistical estimate of the frequency fluctuations of a signal over a given time interval. Short-term stability usually refers to intervals less than 100 s while long-term stability usually refers to time intervals greater than 100 s, more commonly over one day [4].

For typical radio occultation experiments, the actual output frequency, its accuracy or reproducibility are less relevant than frequency fluctuations. Usually, a free-space baseline is established and the changes in frequency (phase) and amplitude introduced by the intervening medium under study, the relative motion between the spacecraft and the receiving station, as well as the noise sources are monitored by high quality receivers at the ground stations.

Factors affecting the stability of an oscillator include: time, temperature, acceleration, and environmental effects such as ionizing radiation, humidity, magnetic field, atmospheric pressure, etc. [5]. The oscillator's behavior is dependent on the applicable temporal scale; the short time scale characterizes the typical noise processes of the type of crystal cut; the intermediate time scale is due to oven fluctuations, and the long-term behavior is due to the aging of the crystal. Aging is the change in the oscillator's frequency due to internal, rather than environmental (external) reasons.

In addition to its effect on the static frequency, the temperature affects the frequency dynamically during periods of warm-up after power is applied to the oscillator. Accelerations due to gravity, acoustic noise, vibration, or shock also affect the frequency stability.

5. Representative Data

Since the first quartz USO was flown on the Voyager spacecraft, the technology has advanced significantly, affording future missions higher sensitivity in reconstructing the temperature-pressure profiles of the atmospheres under study as well as other physical phenomena of interest to Radio Science. The Allan deviation has improved by one order of magnitude in recent USOs. Table 1 shows a tabular summary of representative USOs on deep space missions including key parameters characterizing the oscillators such as mass, size, power, performance measured by Allan deviation, phase noise, drift rates, environmental performance, etc [6]. In some cases, the tabulated data are published specifications, otherwise they are in-flight data. Figure 1 shows the aging data for the Cassini USO from in flight measurements since turn on, which took place a few days after the launch of the spacecraft in October 1997.

Deep Space Mission	**Voyager / Galileo**	**Galileo Probe**	**Mars Global Surveyor**	**Cassini**	**Huygens**
Maker	Frequency Electronics	Frequency Electronics	JHU-APL	JHU-APL	DASA, Germany
Year	1975	1975	1987	1993	1995
Cut	AT	SC	SC	SC	Rubidium
Number of Ovens	2	2	1	1	2
Mass (kg)	1.1		1.3	2	1.9
Power (W)	2.2	1	2.2	2.8	9
Resonator (MHz)	6.38	4.6	4.79	4.79	6835
Nominal Output (MHz)	19.137	23.117	19.144	114.917	10
Aging /24 hours (1)	5 e -11		2 e -11	7 e -11	2 e –9
Temperature /deg C (1)	5 e -12	3 e –12	3 e –12	2 e –12	3e –12
Radiation /rad(1)	2 e -12	2 e –13	1 e –10	1 e –10	
Magnetic field /Gauss(1)	5 e -12	4 e –12	8 e –13	5 e –13	2e-12
Static acceleration /g(1)	1 e -9	1 e –9	3 e -9	1 e –9	4e-12
Harmonic Spurs dBc	-40		-60	-60	-60
Phase noise 1 Hz (dBc)	-100		-110	-85	-75
Phase noise 10 Hz	-108		-125	-110	-95
Allan deviation 1 s(1)	3 e -11	5 e-12	3 e -13	2 e –13	1 e –11
Allan deviation 10 s(1)	4 e -12		1 e -13	1 e –13	5 e –12
Allan deviation 100 s(1)	1 e -12		1 e -13	1 e -13	1 e –12

Table 1: Representative data of parameters characterizing ultra-stable oscillators on deep space missions collected from various sources, in some cases published specifications and, in some cases, in flight data.

(1) Fractional Frequency Uncertainty.

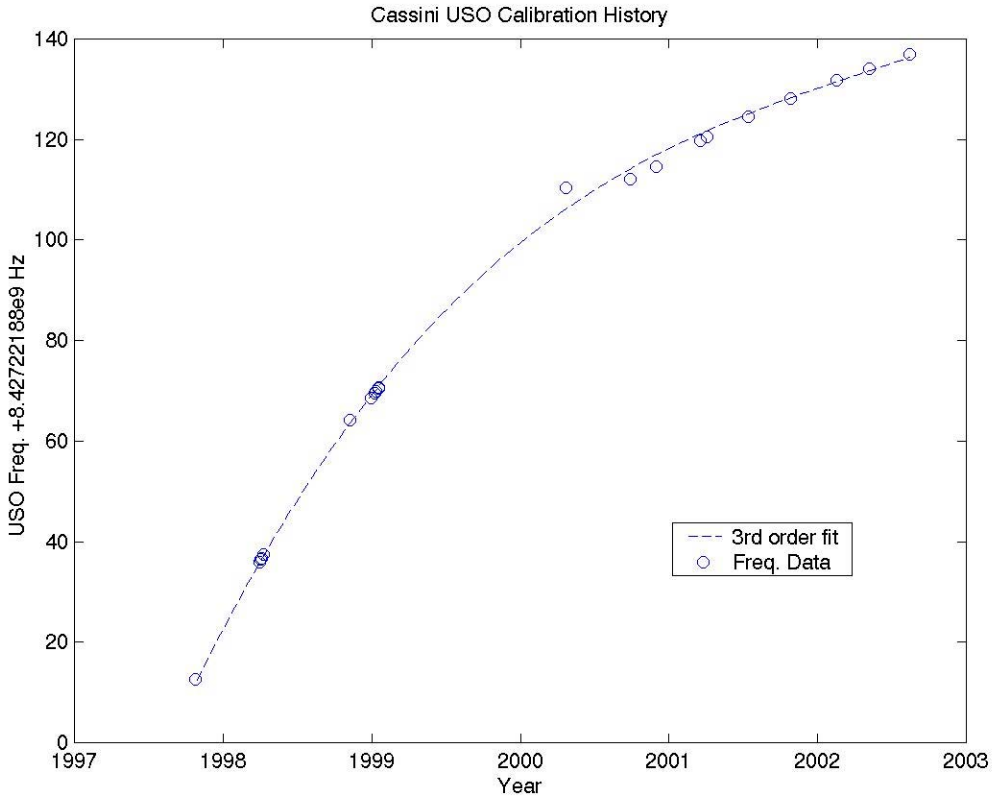

Fig. 1. The frequency down-link at X-band of the Cassini spacecraft when referenced to its on-board ultra-stable oscillator. Data shows drift and aging behavior of the precision quartz oscillator since launch with a line representing a third order fit to the data.

6. Conclusion

Ultra-stable oscillators can enhance deep space missions by providing a stable frequency reference for Radio Science experiments, navigation and communications. The selection of the type of USO for an entry probe must take into account the application requirements as well as operating environment and warm-up time. The technology is mature and several vendors now offer products with good heritage and experience as well as reasonable cost. Future trends in USO technology emphasize miniaturization, making them more attractive for smaller entry probes. Other current research is directed toward synthesized USOs for multi-mission use.

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